

The Activity of Individual Trunk Muscles During Heavy Physical Loading

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The myoelectric activity of ten trunk muscles were recorded, using intramuscular electrodes, when ten subjects made maximal and 50% of maximal static exertions in standing postures. Exertions were made in flexion, extension, and left and right lateral bending. Three heavy-lifting tasks also were studied. A biomechanical model was used to predict the forces in the trunk muscles, and the predictions then were compared to the measurements. The abdominal muscles were all active in attempted flexion, while the erector spinae muscles were inactive. In attempted extension, the erectors were maximally active, but considerable activity was present in the abdominal muscles as well. The highest activity levels recorded in the oblique abdominal muscles were in lateral bending. There were high degrees of correlation between the measured muscle activities and predicted muscle tensions for the erector spinae and rectus abdominus muscles, while the correlation coefficients for the oblique abdominal muscles were lower (0.4–0.7). The study indicates that inclusion of antagonistic activity is an important consideration to improve model predictions. The oblique abdominal muscles appear to be more active, in general, than predicted. For the longitudinal trunk muscles, the predictions are excellent throughout. [Key words: trunk musculature, exertion myoelectric activity, antagonistic activity, biomechanical model]

BIOMECHANICAL ANALYSES of internal lumbar trunk loads developed during performance of various physical tasks have been validated previously using surface myoelectric signal level and intradiscal pressure measurements.^{2,11–15} Excellent correlations between model predictions and experimental measurements have been obtained for sagittally symmetric tasks, while in asymmetric tasks, the correlations have been only moderately good, particularly for the oblique abdominal muscles. For this reason, further research seemed desirable.

There are at least two possible explanations of why the model muscle force predictions may correlate less well with myoelectric measurements in sagittally asymmetric tasks. Myoelectric activities measured at the surface may not adequately differentiate among the activities of the individual muscles over which the sensing electrodes lie, or the model assumptions may be insufficiently realistic.

Surface electrodes pick up activities from a large volume of muscle, with the main contribution from the more superficial slips. The

abdominal muscles are large but flat muscles overlying each other, so that surface electrodes sustain the risk of picking up activities of both the external and internal oblique muscles, as well as the transverse muscles. Similarly, for the erector spinae muscles, the surface electrodes will pick up activities from the entire muscle group. Previous studies have shown that in asymmetric tasks, the activity is different in the sacrospinal and transversospinal parts of the muscles.^{4,7,8} Use of intramuscular electrodes enables the response of individual muscles to be examined. Although needle electrodes are not well suited for kinesiological studies, wire electrodes have been used successfully.

The main purpose of the present study was to examine the validity of a biomechanical model of the lumbar trunk using intramuscular wire electrodes for measurement of trunk muscle myoelectric activities. Activities were measured in relatively strenuous tasks, involving both sagittally symmetric and asymmetric loading, and the measured activities were compared with the muscle contraction forces predicted using a biomechanical model.

SUBJECTS

The study was performed on ten male volunteers with a mean age of 26.5 years (range, 20.5–38.5 years), a mean height of 181 cm (range, 168–192 cm), and a mean weight of 63.5 kg (range, 55–76 kg). All were in good health, and none had previous back injuries or significant back pain.

METHODS

The subjects were asked to perform eight voluntary exertions and three lifting tasks. Voluntary exertions were made in attempted flexion, extension, and left and right lateral bending, both at 100% of maximum voluntary capacity (MVC) and at 50% of MVC. These tasks were performed in the upright standing posture, in a reference frame designed to allow measurement of configuration data. The subjects' pelvises were strapped to a support board, and foot positions were prescribed. Loading was through a harness strapped to the trunk at the T7 level. The subjects were asked to pull isometrically in the four directions, first to MVC and then to 50% of that value. The exerted forces were measured with a strain-gauged load cell, and indicated to the subjects by a meter.

The three lifting tasks involved lifting a box placed 10 cm above the floor. The box was placed directly anterior to the subject (the box then weighed 250 N) and at 45° to the right and to the left (at which time the box weighed 200 N). The distance from the box to the approximate center of the subject's lumbar spine was 50 cm. When lifting, the subjects had identical and symmetric foot position. In the lateral lifting tasks, the feet were facing forward and the subjects were facing the load (a combination of bending, lateral bending, and twisting).

Data Measurement. Two types of measurements were made. Configuration data were taken to locate approximately the mass centers of the head, upper limbs, and trunk, and the lines of action and moment arms of the external loads. Myoelectric activities in trunk muscles were measured with intramuscular electrodes.

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Measurements of Myoelectric Activity. The myoelectric signals were picked up by ten fine-wire monopolar electrodes. The muscles studied were the multifidus (EM) and longissimus (EL) portions of the erector spinae; and the rectus abdominus (RA), obliquus externus (OE), and obliquus internus (OI) abdominal wall muscles. Electrodes were placed on both left (L) and right (R) sides of the trunk. The erector spinae muscle electrodes were placed at the L3 spinous process level as previously described by Jonsson.⁷ The rectus abdominus electrodes were inserted 3 to 4 cm inferior to the umbilicus level, in the center of the muscle belly. The electrodes for the internal obliques were placed 5 cm above the anterior iliac spine at approximately the L3 level. The needle was angled about 45° from this insertion distally. The external oblique muscle electrodes were placed 3 to 4 cm above the midpoint of the iliac crest. Previous cadaver studies by the authors of fine-wire electrode insertion into the abdominal muscles have shown that these muscles can be reproducibly reached by this method. A reference surface electrode was placed over the spinous process of the T12 vertebra.

Biomechanical Analyses. The contraction forces in the trunk muscles needed to perform each task and the compression and shear loads imposed on the spine were computed for each subject by biomechanical analyses. Each analysis was based on the requirement that all body segments superior to an imaginary transverse cutting plane at the L3 level of the spine must remain in equilibrium during task performance. The analysis was made in two steps. First, the net lower-trunk support reaction needed for equilibrium was computed. Then, the trunk muscle contraction forces that could supply that net reaction and the resulting spine compression and shear loads were estimated.

Computation of the net reaction requires knowledge of the magnitudes of the externally applied loads and the weights of all body segments superior to the cutting plane. The externally applied loads were the measured applied forces or the weights lifted. The weights of the head, each arm, and the trunk were assigned in proportion to the subject's body weight, based on the data of Clauser et al.³ The points at which these forces and weights were applied were available for each task and each subject from the configuration measurements. Once all of these data were entered into the six equations expressing the requirements for equilibrium, the six components of the net reaction were computed.

The trunk muscle contraction forces and the spine compression and shear loads were calculated from the net reaction using biomechanical models of the L3 cross-section and solving the model equations by optimization techniques. The anatomic data used in the model were obtained from Eycleshymer and Schoemaker,⁵ and are described in detail by Schultz et al.¹⁴ The major muscle groups spanning the lumbar region were represented by 11 bilateral pairs of single muscle equivalents: the rectus abdominus muscles (R_L and R_R); the lateral (EOL_L and EOL_R) and the medial (EOM_L and EOM_R) external oblique abdominal muscles; the lateral (IOL_L and IOL_R) and the medial (IOM_L and IOM_R) internal oblique abdominal muscles; the psoas (P_L and P_R); the quadratus lumborum (Q_L and Q_R); the latissimus dorsi (L_L and L_R); and the multifidus (EM_L and EM_R) longissimus (EL_L and EL_R), and iliocostalis (EI_L and EI_R) groups of the erector spinae muscles.

The L3 spine motion segment was assumed to resist compression, lateral shear, and anteroposterior shear, but to have no significant moment resistance. Abdominal cavity pressurization was not accounted for, because in isometric performances of the type studied here, it does not show a consistent relationship with the loads imposed on the spine by task performance and has been estimated to provide a mean spine compression relief of only approximately 15%.¹¹ The L3 cross-sectional anatomy was scaled in proportion to the L3 level trunk width and depth of each subject. This scaling was used to locate single equivalent muscle centroids and to compute the cross-sectional area for each muscle represented.

The optimization scheme used to calculate internal forces minimized approximately the maximum required muscle contraction

intensity (stress).¹⁴ To achieve this, the maximum allowed contraction intensity was, in effect, set to 10 kPa, and a solution was sought by linear programming so as to minimize the compression force on the spine. If no solution was available, the allowed intensity was incremented by 10 kPa, and a solution was again sought. This intensity incrementation procedure was iterated until a solution was found. Use of this optimization scheme keeps antagonistic muscle activity to a minimum, although it calls on nearly every muscle that can contribute to an activity to do so at nearly equal contraction intensities.

Signal Processing and Evaluation Procedure. The electrode signals were fed to preamplifiers in a box suspended close to the subjects. The signals were amplified further in main amplifiers and recorded on magnetic tape. During recording, the signal quality was checked continuously on an oscilloscope screen. Recordings were made for 15 seconds for each task. A minimum of 3 minutes rest was allowed between each task, or more if the subject felt fatigue. For analysis, the signals were played back and fed to a multi-channel RMS detector unit, and further to the analog-to-digital converter of a computer. The RMS detector included low-pass filters with a 3-dB frequency limit set at 0.8 Hz. The analog-to-digital conversion rate was 6 Hz. The gain was determined for each channel and each subject, and the signal amplitude data were expressed in microvolts.

Statistical Analysis. For each of the 11 tasks, means and standard deviations of the myoelectric signal amplitudes were calculated for the ten subjects at each electrode location. Similarly, the means for the ten subjects of each force estimate in each of the muscle equivalents were computed. Linear regression analysis then was used to determine the relationship between the force estimate means and the myoelectric signal level means.

RESULTS

The exerted forces measured at the load cell and the computed moments about the center of the L3 intervertebral disc are given in Table 1 for the eight exertion tasks in the upright position. There is considerable variation between subjects with maximum flexion forces ranging from 320 to 750 N (mean, 547 N), extension forces from 420 to 1,000 N (mean, 664 N), left lateral bending forces from 380 to 630 N (mean, 469 N) and right lateral bending forces from 360 to 700 N (mean, 507 N). The mean measured myoelectric activities in those exertions are given in Table 2, along with the computed individual muscle forces. The abdominal muscles were all quite active in attempted flexion, while the ESM were inactive. The highest recorded activity of the rectus abdominus was found in this task. In attempted extension, on the other hand, the ESM were very active, but considerable activity was present in the abdominal

Table 1. Forces Exerted and Their Computed Moments at the L3 Level

Loading	MVC* (%)	Mean exerted force (SD)	Mean flexion moment
Flexion	100	547 (132)	153
	50	276 (72)	77
Extension	100	664 (179)	186
	50	332 (90)	93
L. lateral	100	469 (85)	131
	50	234 (41)	66
R. lateral	100	507 (114)	142
	50	253 (58)	71

*MVC = maximum voluntary contraction.

Table 2. Mean Measured Myoelectric Activities and Predicted Muscle Tensions in the 11 Different Tasks

	MVC* (%)	Longissimus				Multifidus				Rectus A				Obliquus I				Obliquus E				
		L†		R†		L		R		L		R		L		R		L		R		
		N‡	V‡	N	V	N	V	N	V	N	V	N	V	N	V	N	V	N	V	N	V	
Loading																						
Flexion	100	0	56	0	56	0	60	0	51	258	640	258	734	358	571	359	548	269	384	270	372	
	50	0	27	0	20	0	26	0	20	132	266	132	307	175	273	176	233	109	172	109	159	
Extension	100	650	1041	650	864	325	1139	325	1107	0	241	0	234	0	401	0	359	0	485	0	409	
	50	332	442	332	336	166	526	166	492	0	90	0	87	0	135	0	96	0	134	0	103	
L. bending	100	326	717	0	58	54	377	0	63	125	300	0	131	179	1100	0	93	158	717	0	138	
	50	147	261	0	22	2	95	0	27	56	94	0	57	91	350	0	38	81	246	0	52	
R. bending	100	0	73	319	587	0	87	16	449	0	153	123	394	0	114	176	769	0	158	155	729	
	50	0	30	164	291	0	31	2	204	0	57	62	102	0	56	98	273	0	73	88	275	
Lifting																						
Anterior		429	415	429	333	215	414	215	387	0	115	0	140	0	146	0	127	0	151	0	144	
R. lateral		296	387	219	290	148	406	137	337	0	141	0	140	157	204	0	144	141	159	0	155	
L. lateral		110	319	266	284	104	321	130	250	0	131	5	116	0	166	143	192	0	150	126	147	

*MVC = maximum voluntary contraction.
 †L = left; R = right.
 ‡N = Newton; V = microvolt.

Table 3. Mean Myoelectric Activities as a Percent of the Highest Measured Muscle Activity for Each Muscle

	MVC* (%)	Longissimus		Multifidus		Rectus A		Obliquus I		Obliquus E	
		L†	R†	L	R	L	R	L	R	L	R
Attempted movement											
Flexion	100	5	7	5	5	100	100	52	71	54	51
	50	3	2	2	2	42	42	25	30	24	22
Extension	100	100	100	100	100	38	32	36	47	68	56
	50	42	32	44	14	12	12	12	12	19	14
L. bending	100	69	7	33	6	47	18	100	12	100	19
	50	25	3	8	2	15	8	32	5	34	7
R. bending	100	7	68	8	41	24	54	10	100	22	100
	50	3	34	3	18	9	14	5	36	10	38
Lifting											
Anterior		40	39	36	35	18	20	13	17	21	20
R. lateral		37	34	36	30	22	20	19	19	22	21
L. lateral		31	33	28	23	21	16	15	25	21	20

*MVC = maximum voluntary contraction.

†L = left; R = right.

muscles as well, and thus was not predicted by the model. The highest activity levels in the oblique abdominal muscles were recorded in lateral bending.

Table 3 shows that the activities of the abdominal muscles in maximum extension varied from 32% to 68% of the highest myoelectric levels recorded in those muscles. In attempted left and right lateral bending, the ipsilateral muscles were always quite active, but there also was some activity in the contralateral muscles. The ipsilateral oblique abdominal muscles were more active in lateral bending than in any of the other tasks, while the contralateral oblique muscles were active at about 10% to 20% of their highest myoelectric activities. In lateral bending, the ipsilateral rectus abdominus was active at about 50% of its highest recorded level, the longissimus muscles at almost 70%, and the multifidus muscles at about 40%. Contralateral activity was about 20% in the rectus, but only 7% in the erector spinae muscles.

In the lift experiments, all muscles were active in all three tasks and at similar levels of activity. The model predictions of no rectus abdominus activity in any of these tasks and no oblique abdominal muscle activities in anterior ipsilateral lifting were not borne out by the measurements.

There were high degrees of correlation between the measured muscle activities and the predicted muscle tensions for the longissimus, multifidus, and rectus abdominus muscles, while the correlation coefficients for the oblique abdominal muscles were lower, between 0.4 and 0.7 (Table 4). Table 4 presents calculations based on the results obtained in only the flexion-extension experiments,

in all the attempted exertions in the upright posture (eight tasks), and in all tasks studied (11 tasks). In the erector spinae and the rectus abdominus, the correlation coefficients are similar for all three calculations, but this was not the case for any of the oblique abdominal muscles. Figure 1 illustrates the relationship of measured myoelectric activity and predicted muscle forces for the left side multifidus and longissimus muscles.

DISCUSSION

The maximum voluntary forces exerted and their moments about the L3 level in this study are similar to those previously reported by Schultz et al.¹⁵

The general pattern of myoelectric activity is also in agreement with previous investigations. Thus, in attempted extension, the main muscles that were active were the erector spinae, as previously described by Jonsson,⁷ Morris et al.,⁸ and Pauly.⁹ However, the high activity levels of the abdominal muscles during attempted extensions was a surprise. Perhaps these muscles were used to raise the intra-abdominal pressure. Gracovetsky et al.⁶ have suggested that the abdominal muscles may aid in creating an extension moment by exerting a pull at the lateral margins of the thoracolumbar fascia. Another possibility is that the abdominal muscles, particularly the rectus abdominus, were active to stabilize the trunk.

In attempted flexion, on the other hand, all of the abdominal muscles were active, while the ESM were almost silent. This would be expected from mechanical considerations and is in agreement with the findings of Schultz et al.¹⁵

Table 4. Correlation Coefficients Between the Predicted Muscle Tensions and the Measured Myoelectric Activities. Separate Calculations Were Made Over the Four Flexion-Extension Tasks (40 Data Pairs), the Eight Resist Tasks (80 Data Pairs), and all tasks (110 Data Pairs)

Loading	Correlation Coefficients Between Mean Predicted Tensions and Mean Measured Activities									
	Longissimus		Multifidus		Rectus A		Obliquus I		Obliquus E	
	L*	R*	L	R	L	R	L	R	L	R
Flexion-extension	0.99	0.99	1.00	1.00	0.92	0.94	0.72	0.73	0.17	0.32
All attempted exertions	0.98	0.97	0.99	0.93	0.92	0.94	0.38	0.40	0.61	0.70
All tasks	0.93	0.93	0.90	0.93	0.90	0.93	0.58	0.68	0.43	0.51

*L = left; R = right.

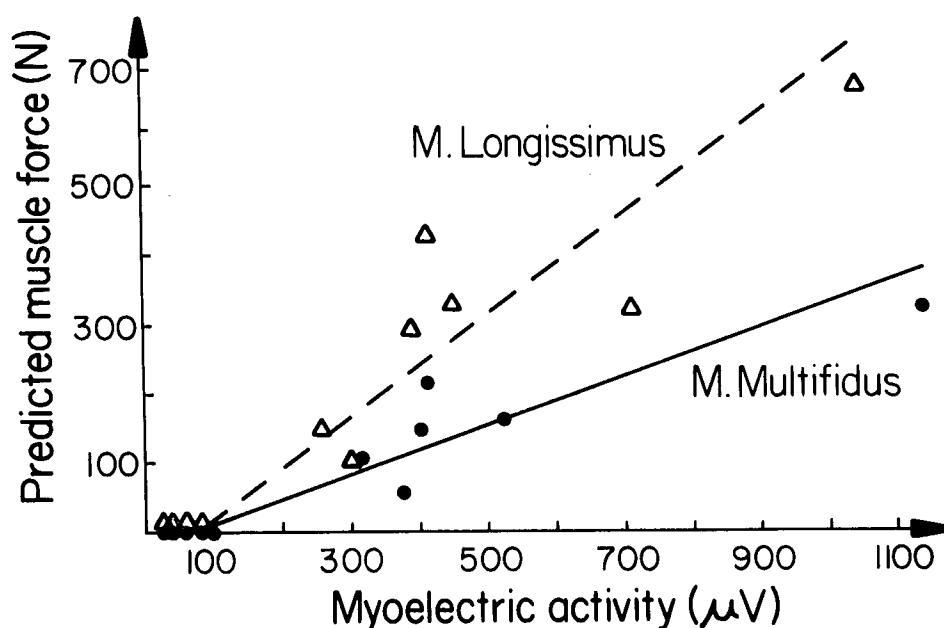


Fig 1. Relationship of mean myoelectric activities and predicted muscle forces for the longissimus and multifidus parts of the erector spinae muscles.

Activity in the ipsilateral muscles was predictably associated with attempted lateral bending. This was true for all of the muscles studied, both anterior and posterior. In the oblique abdominal muscles there was little difference in myoelectric activity between the external and internal parts, while in the ESM, a significant difference was found between the multifidus and longissimus muscles. This agrees with the findings of Jonsson⁷ and Andersson et al¹ that the more lateral a muscle is to the spine, the higher its myoelectric activity level in lateral bending. Again, this is expected from mechanical considerations, assuming that the level of myoelectric activity is related to the level of muscle tension.

The two lifting tasks in the study are less well defined, with respect to the back posture, than the upright standing tasks. The position of the load relative to the subject was used to reproduce the task. It is, however, possible to perform it with various spine postures. The body configuration measurements will locate the mass centers and L3 in the sagittal and frontal plane, but, of course, will give no detailed information on the spine configuration. The correlation coefficients obtained in these tasks for the erector spinae muscles were as good as those in lateral bending, but were slightly less good than those in the sagittally symmetric positions; the opposite is true for the oblique abdominal muscles.

The excellent correlation between predicted muscle tensions and measured myoelectric activities in the longitudinal trunk muscles (erector spinae and rectus abdominus) confirms findings of previous studies.^{2,11-15} The model does predict tensions in these muscles over a large force range with apparent good precision.

The poorer correlations obtained for the oblique muscles also were in agreement with findings from our previous studies, which were obtained using surface electrodes. Thus, the use of surface electrodes was apparently not the reason for those relatively weak correlations. This finding seems important in directing future research regarding loads on the spine. It indicates that either the muscle tension/myoelectric activity relationship is not, as assumed, monotonic and close to linear in those muscles; or that some of the assumptions made in the model calculations are unrealistic.

Other studies performed in our laboratory have shown a monotonic and close to linear relationship between trunk torque produc-

tion and the myoelectric activity of the abdominal muscles.¹⁰ Studies of other muscles have shown, however, that non-linearities can be expected. Further studies are needed to resolve that aspect of the model assumption. The abdominal muscles are large and flat muscles, and electrodes within them pick up activity from a limited area. The electrodes were placed as described to ensure that they were, in fact, located within the muscle they were intended to monitor. As a result, however, activity in the external oblique muscles was recorded at the posterior axillary line (lateral on the trunk), while that of the internal obliques was recorded at the mamillary line (anterior). This may help explain differences between predictions and measurements, particularly in lateral bending, should the oblique muscles not be active equally over their entire volume.

Major assumptions made in the model were that antagonistic activity occurred minimally, and that the intra-abdominal pressure and soft-tissue bending resistances had little effect. It is clear that the assumption of minimal antagonistic activity was not always valid. The left and right internal and external oblique muscles were all active in all of the 11 task performances. In future models, therefore, use of antagonists needs to be accounted for by use of objective functions other than those used here. The antagonists might be assumed to be active in some proportion to the agonist activity, for example. Experiments clarifying agonist-antagonist relationships are necessary.

The issue of whether or not the intra-abdominal pressure should be incorporated in the model also should be addressed. We did not measure intra-abdominal pressure in our subjects. Based on our previous studies, incorporation of such pressures could improve predictions, but only to a limited degree.

The cross-sectional anatomic data used in the model are currently being updated, as new information based on current imaging data is being made available.

In spite of the shortcomings of the model, the correlations obtained were generally reasonable. The oblique abdominal muscles, while important, seldom dominate total contributions to the loads imposed on the lumbar spine by performance of physical activities. Thus, the model predictions were qualitatively correct as to the general pattern of muscle activity.

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